Viscosity measurement of liquid lithium by the damped torsional oscillation method: experimental study and error analysis*

Zu-Long Hao,[1,†] Tao Yang,[1] and Yan He[2]

[1]*School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China*

[2]*CGN Lufeng Nuclear Power Co. Ltd, Shanwei 516600, China*

Accurate measurement of the viscosity parameters of lithium metal under high-temperature operation condition is important for the thermal hydraulic model calculation of lithium-cooled nuclear reactors. In order to study the mechanism of the measurement error generation of viscosity of liquid lithium, an oscillating cup viscometer based on Shvidkovskiy algorithm was developed for the liquid lithium over a temperature range from 200℃ to 650℃. Then the experimental errors analysis and uncertainty calculation were carried out. The results show a very low uncertainty with an average deviation of 1.82% for kinematic viscosity experiments and 1.70% for dynamic viscosity experiments. Moreover, we found that the experimental deviation using 0.15 mm diameter of molybdenum wire was nearly half of that of 0.18 mm diameter wire. It shows that appropriately reducing the diameters of molybdenum wire can improve the accurate measurement of viscosity for oscillation measurements.

Keywords: Liquid-metal coolant; viscosity; lithium; damped torsional oscillation method; error analysis

1 Introduction

Among the alkali metals, liquid lithium is suitable to be used as coolant for space reactors because of its exceptional properties, such as high operating temperature, excellent thermal conductivity and low density [1]. In conceptual design stage of lithium-cooled reactors, the thermophysical properties of liquid lithium under different operation temperature serve as crucial basic data. And viscosity is one of the most important thermophysical parameters that directly impact the flow characteristic of the coolant, subsequently influencing the cooling efficiency of the reactor system. However,

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† Corresponding author, Hao Zu-Long; No.2, Beinong Road, Huilongguan, Changping District, Beijing; 010-61771677; haozulong@ncepu.edu.cn

accurate measuring the viscosity of liquid alkali metals is a challenging work due to their high melting point, low viscosity and chemical activity.

Current viscosity measurement methods include the capillary method, oscillating vessel method, rotational method and oscillating plate method [2]. For the viscosity measurement of liquid lithium, Andrade [3] employed the oscillating sphere method to measure the viscosity of liquid lithium within a certain temperature range, starting from near the melting point and extending upwards. Ban [4] measured the viscosity of molten lithium's separated isotopes by observing the damping oscillation of a torsion pendulum. Ito [5] measured the viscosity of liquid lithium in the temperature range of 464 to 923 K using an oscillating cup viscometer, relying on the Kestin-Newell equation to achieve measurement accuracy of ±3%. Similarly, Novikov[2], Rigney[6], and Achener [7] et al. also opted for the oscillating method for their respective viscosity measurements.

Most experiments on the viscosity testing of liquid lithium are still rooted` in the mid to late 20th century. The deviations in measuring the same physical properties among different researchers can reach 15 to 25%. Achener's experimental results exhibit not only an average deviation of 18% but also a deviation of more than 25% compared to other researchers' results.

In sharp contrast to the challenges faced in measuring other liquid metals, Zhu [8] investigated the use of an oscillating cup viscometer based on the Shvidkovskiy algorithm and time-resolved reflection measurement to measure the viscosity of pure aluminium in the temperature range from the melting point to 1300 K, achieving a remarkably low uncertainty of 2.1% for dynamic viscosity measurements. Patouillet [9] successfully measured the dynamic viscosity of liquid tin in the temperature range of 506-2135 K and liquid lead in the temperature range of 710-1770 K employing an oscillating cup viscometer, maintaining a relatively low uncertainty of approximately 2.5%.

Hence, to refine the measurement methods and associated parameters pertaining to the viscosity of liquid lithium, analyse the factors contributing to the measurement deviations of liquid lithium viscosity, and uncover the variation patterns of liquid lithium viscosity under space environments, an experimental study on the viscosity of liquid lithium based on the damped torsional oscillation method is conducted in this paper. An oscillating-cup viscometer is developed for measuring the viscosity of high-temperature liquid metals. Employing this device, the viscosity of liquid lithium within a temperature range of 200°C to 650°C is measured, revealing the variation pattern of

the kinematic viscosity of liquid lithium with temperature. Additionally, the impact of using molybdenum wires with different diameters on the viscosity measurement deviations is analysed. The analysis underscores that the factors with the most significant influence on measurement deviations are the oscillation periods T and t_{AB}, with the selection of molybdenum wires with different diameters directly affects the motion period of the suspension system. The average deviation of the kinematic viscosity experimental results is 1.82%, and the average deviation of the dynamic viscosity experimental results is 1.70%. The kinematic and dynamic viscosities of liquid lithium decrease as the temperature rises. The data deviation of dynamic viscosity is reduced to ±2.6%, which is comparable to the measurement deviations of other liquid metals. This study offers valuable insights and serves as a reference for advancing testing methods and techniques of fundamental properties of liquid metals, particularly lithium.

2 Analytical model for viscosity of liquid lithium

As mentioned above, the acknowledged experimental method for studying the viscosity of liquid metals is oscillation method. Considering the difficulty of fabricating the experimental setup and the convenience of experimental operations, the hanging-type measurement method is selected for this research [10-13]. The fundamental principle of the hanging-type oscillation method is illustrated in Fig. 1.

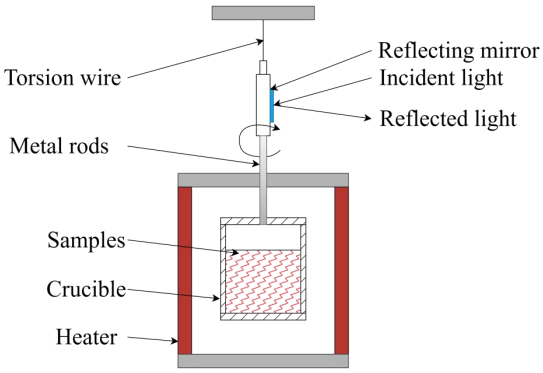

Fig. 1 Schematic diagram of the suspended oscillation method

The Shvidkovskiy model, which is applicable to the oscillation method, was chosen to calculate the kinematic viscosity with the following formulas:

$$\nu = \frac{I^2\left(\delta - \delta_0 \frac{T}{T_0}\right)^2}{\pi (m R^2) T W^2} \tag{1}$$

$$W = 1 - \frac{3}{2}\Delta - \frac{3}{2}\Delta^2 - a + (b - c\ \Delta)\frac{2p\ R}{H} \quad (2)$$

$$\Delta = \frac{\delta}{2\pi} \quad (3)$$

$$y = R^{\ 2}\frac{2\pi}{T\nu} \quad (4)$$

where I is the total moment of inertia, T is the period of rotation, δ is the logarithmic decrement, the subscript 0 denotes the initial parameters and m stands for the mass of liquid metal. R is the inner diameter of the crucible, H is the height of the liquid sample to be measured, and ρ is the density of the liquid, if $p = 1$ indicates that the crucible is partially filled with liquid, while $p = 2$ indicates that the crucible is filled. W is the correction coefficient for different measurement states, and in its calculation, a, b, and c are instrument-related parameters. The estimation methods for these three parameters can be found in reference [14], where coefficients a, b, and c are functions of y. The calculation sequence of kinematic viscosity is shown in Fig. 2.

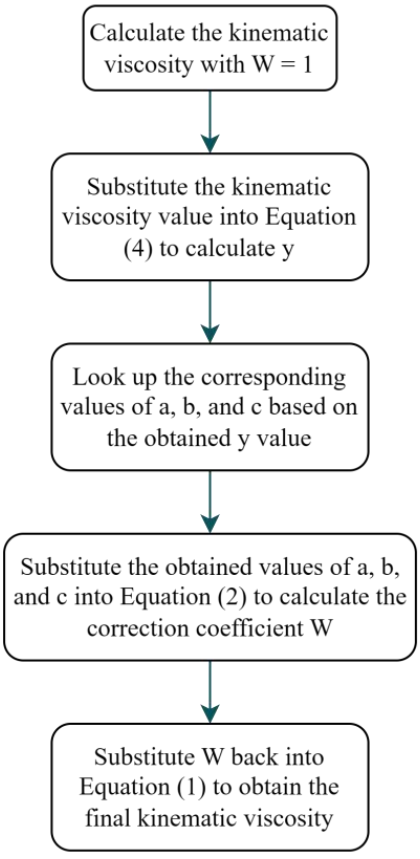

Fig.2 Flow chart of the kinematic viscosity calculation

Furthermore, we can obtain the dynamic viscosity as following:

$$\eta = \rho \bullet \nu \quad (5)$$

The total moment of inertia I is determined through multiple observations of the oscillation period of the oscillation system. The formula employed for this purpose is as follows:

$$I = I_i + I_0 \tag{6}$$

where I_0 and I_i represent the rotational inertia of the system before and after adding the standard counterweight, respectively. The calculation formulas are as follows:

$$I_i = \frac{m}{2}(R_1^2 + R_2^2) \tag{7}$$

$$I_i = -I_0 + D\frac{T_i^2}{4\pi^2} \tag{8}$$

Where m represents the mass of the standard cylindrical load, R_1 and R_2 are the inner and outer radii of the standard cylindrical load, respectively, and D is the elastic constant of the molybdenum wire. T_i denotes the time interval of the i-th motion cycle, where each cycle of the laser spot is divided into four parts: AA, AB, BB, and BA. Therefore, the calculation formula for T_i is given as:

$$T_i = t_{AA} + t_{AB} + t_{BB} + t_{BA} \tag{9}$$

The logarithmic decrement δ measurement method is performed by measuring the time interval between the reflection of an oscillating laser beam passing through two laser receivers [15-16]. The calculation formula is given as:

$$\delta = \frac{\ln\left[\frac{\sin\left(\frac{2\pi t_{(AB,i+n)}}{T}\right)}{\sin\left(\frac{2\pi t_{(AB,i)}}{T}\right)}\right]}{n + \left(t_{(AB,i+n)} - t_{(AB,i)}\right)/T} \tag{10}$$

where $t_{(AB,\,i)}$ is the time interval of AB during the i-th measurement cycle, while $t_{(AB,\,i+n)}$ denotes the time interval during the $(i+n)$-th measurement cycle. T stands for the average period of $2n$ consecutive measurements. Over these $2n$ measurement cycles, a set of logarithmic decrement values (δ_1, δ_2, …, δ_n) is obtained, from which the average logarithmic decrement δ is calculated.

The formula for the initial logarithmic decrement δ_0 is given as:

$$\delta_0 = \frac{c_0}{2I_0\omega_0} \tag{11}$$

where $c_0$represents the initial damping coefficient of the suspension wire, k is the stiffness coefficient of the suspension wire, and ω_0 denotes the initial angular frequency.

$$\omega_0^2 = \frac{k}{I_0} - \left(\frac{c_0}{2I_0}\right)^2 \quad (12)$$

The initial logarithmic decay rate δ_0, can be calculated employing the following equation:

$$\delta_0 = \frac{\pi c_0}{\sqrt{Dk T_i^2 - 2\pi^2 k m \left(R_1^2 + R_2^2\right)}} \quad (13)$$

Based on Eqs. (1, 2, 4), it can be derived as following:

$$\nu = \frac{D T_i^2 \left(\frac{\ln\left[\sin\left(2\pi t_{(AB,i+n)}/T\right)/\sin\left(2\pi t_{(AB,i)}/T\right)\right]}{n + \left(t_{(AB,i+n)} - t_{(AB,i)}\right)/T} \right)^2 T_0}{4\pi^3 m^2 R^2 T W^2} \quad (14)$$

$$W = 1 - a + \frac{2b p R}{H} - \left(\frac{3}{4} + \frac{c p R}{H}\right)\frac{\delta}{\pi} - \frac{3}{8}\left(\frac{\delta}{\pi}\right)^2 \quad (15)$$

$$y = \frac{8\pi^4 m^2 R^4}{D T_i^2 \left(\frac{\ln\left[\sin\left(2\pi t_{(AB,i+n)}/T\right)/\sin\left(2\pi t_{(AB,i)}/T\right)\right]}{n + \left(t_{(AB,i+n)} - t_{(AB,i)}\right)/T} \right)^2 T_0} \quad (16)$$

The dynamic viscosity is calculated as:

$$\eta = \frac{\rho D T_i^2 \left(\frac{\ln\left[\sin\left(2\pi t_{(AB,i+n)}/T\right)/\sin\left(2\pi t_{(AB,i)}/T\right)\right]}{n + \left(t_{(AB,i+n)} - t_{(AB,i)}\right)/T} \right)^2 T_0}{4\pi^3 m^2 R^2 T W^2} \quad (17)$$

As stated in Eq. (14), the input for the Shvidkovskiy model to calculate the kinematic viscosity includes parameters such as the wire elastic coefficient D, the time interval T_i of the i-th motion cycle, the time intervals $t_{(AB,\,i)}$ and $t_{(AB,\,i+n)}$ between the i-th and $(i+n)$-th measurement cycles for AB, the average cycle T, the idle cycle T_0, the inner and outer radii R_1 and R_2 of the standard cylindrical load, the initial damping coefficient c_0 of the wire, the stiffness coefficient k of the wire, the mass m of the liquid under test, the inner

diameter R of the crucible, and so on. Once these parameters are determined, the final viscosity can be obtained.

3 Experimental system and sample treatment

3.1 Experimental Setup

The experimental setup is a suspended high-temperature molten metal torsional oscillation viscometer designed based on the Shvidkovskiy formula with a correction factor. As illustrated in Fig.3, it primarily consists of an oscillation system driven by a stepper motor, a heating system, and a measurement system comprising a laser transmitter and receiver.

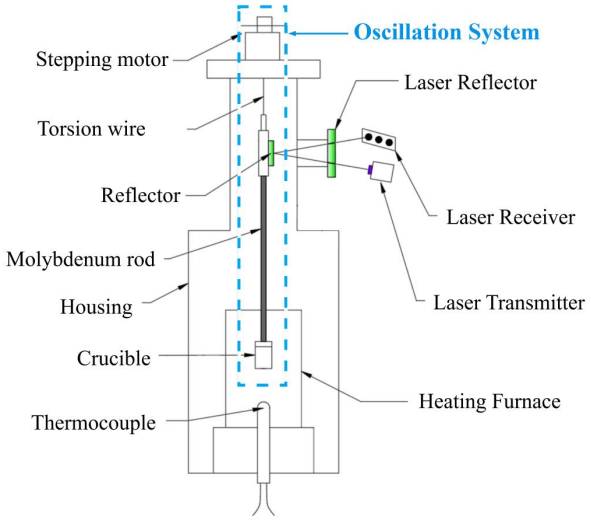

Fig. 3 Schematic diagram of the viscosity experimental setup

(1) Oscillation System. As depicted in Fig.4, the oscillation system is enclosed within the blue box. The crucible, made of stainless steel 316L, has an inner diameter of 13 mm and a height of 40 mm. The metal lithium, after careful treatment to remove impurities, is placed in the crucible. The suspension wire is constructed from molybdenum, a metal with a high melting point, high strength at elevated temperatures, and a low coefficient of expansion. This ensures stability in dimensions under high temperatures, facilitating the measurement of a stable and precise logarithmic decay rate, thus reducing experimental errors.

(2) Heating System. The heating and temperature control system comprises a heating furnace and a thermocouple. The crucible rotates in the central chamber of the furnace, with a narrow gap between the crucible's outer wall and the heating elements. This gap is filled with refractory insulation materials to

minimize heat loss during experiments. The temperature controller employs a Yudian AI-516 intelligent temperature control device, capable of precisely regulating the furnace's heating rate to achieve a given heating and cooling curve slope. This allows the furnace to rapidly reach the desired temperature and maintain it for a set duration, while compensating for heat loss above the crucible. Testing has confirmed that the heating system maintains a temperature error within ±1°C.

(3) Measurement System. Laser oscillation detection is accomplished by the measurement system. The laser source is positioned approximately 1.7 m from a mirror mounted on the suspension system, and the distance between laser receivers A and B is 55 cm. A helium-neon laser is chosen as the laser source, while photodiodes serve as the photoelectric sensors. Experimental results indicate that the system achieves a time detection accuracy of 0.1 ms, improving the measurement precision of the time and the logarithmic decay of the oscillation. Continuous time interval signals are transmitted to a computer via Bluetooth. The equipment diagram is shown in Fig.5.

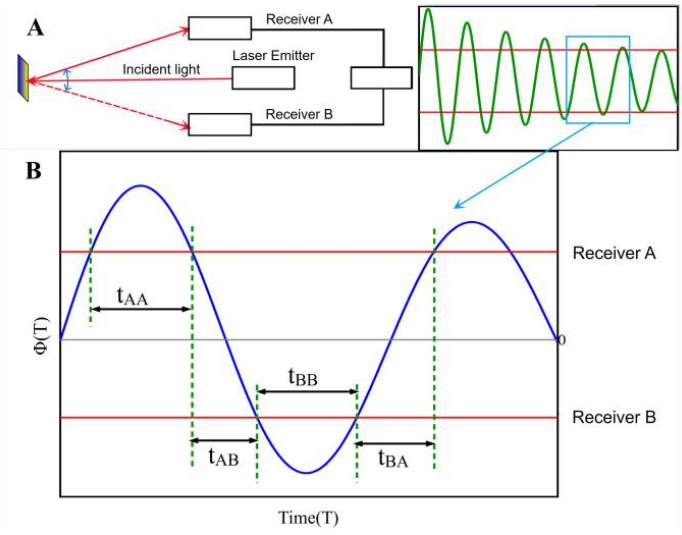

Fig. 4 Oscillation Decay Curve and Time Interval of One Motion Cycle; Φ(T) is the angular displacement of the crucible from equilibrium.

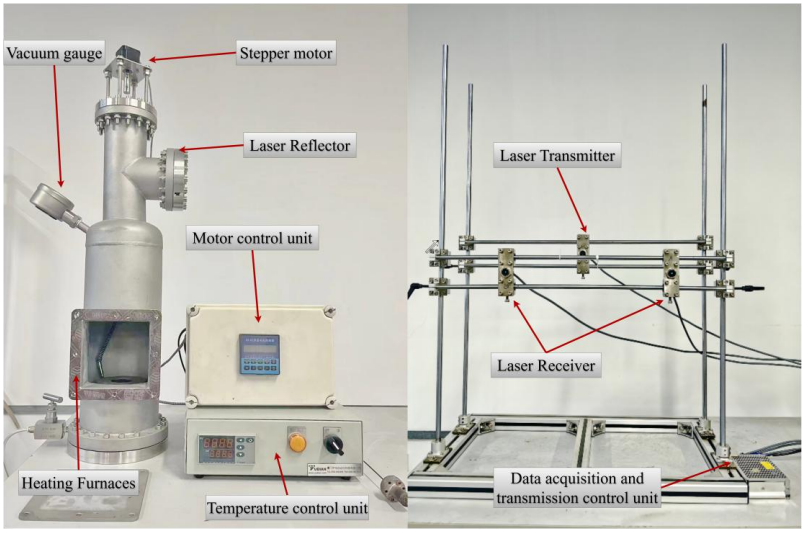

Fig. 5 Viscosity measurement test system for liquid lithium

3.2 Lithium sample treatment

The crucible used for the experiment was 13.24 mm in diameter and 40 mm in depth, and the purity of the lithium pellet was 99.974% with 260 ppm of total metallic impurities. The diameter of the crucible used for the experiment was too small to remove the impurities directly with a steel spoon. To ensure the purity of the experimental liquid lithium, the lithium grains needed to be treated.

The surface impurities of the lithium grains were removed cleanly with a knife in an argon glove box, and the comparison of lithium grains before and after treatment is shown in Fig.6. No. 1 in the figure is the original lithium grains purchased, the surface shows grey black, no metallic lustre. If melted in this state, it would be difficult to remove in the experimental crucible. If the impurities are not removed before the experiment, the liquid lithium cannot contact and wet the experimental crucible, and when the oscillation system drives the crucible to swing back and forth at the beginning of the experiment, the liquid lithium and the inner wall of the crucible will slip, resulting in a small experimental result.

Fig. 6 Comparison of lithium particles before and after treatment

Lithium grains need to be melted in the experimental crucible after cutting, as shown in Fig.7. The crucible was placed in a heating furnace and heated to 400~450°C and baked for about 1h. The cut lithium grains were put into the crucible, and the surface tension of liquid lithium was destroyed with the handle of a stainless-steel spoon, so that the liquid lithium completely wetted the inner wall of the crucible and then cooled, and the lithium metal was cooled and solidified, and then the crucible was sealed using bolts.

Fig.7 Lithium pellet melting and encapsulation in crucible

4 Experimental error analysis

4.1 The effect of molybdenum wire diameter

The period of oscillation of the oscillation system of the experimental setup is determined by two parameters, one is the rotational inertia of the reflector, molybdenum rod, and crucible hardware at the lower end of the suspension system mount, and the other is the diameter of the suspension wire. The moment of inertia is determined by the structure of the hardware such as mass and mass distribution, and when the mounted mass is certain, a change in the diameter of the suspension wire affects the rotation period of the suspension system.

Among the input parameters, the inner and outer radii R_1 and R_2 of the standard cylindrical load, the mass of the liquid to be tested (m), and the inner diameter of the crucible (R) are independent of the suspension wire diameter. The differences in the initial damping coefficient (c_0), stiffness coefficient (k), and elastic coefficient (D) of the suspension wire between 0.15mm and 0.18mm diameter molybdenum wires are negligible. Through measurements, the elastic constant (D) for the 0.15mm diameter molybdenum wire was found to be 1.86×10^{-5} kg·m^2, while the elastic constant for the 0.18mm diameter molybdenum wire was 7.73×10^{-5} kg·m^2. Molybdenum wires with diameters of 0.15mm and 0.18mm were installed in the suspension system, and standard cylindrical loads with a thickness of 11mm, an inner radius of 1.34mm, and outer radii of 7.53mm, 10.02mm, 12.52mm, 14.95mm, and 17.45mm were successively installed on the suspension system. Each experiment was conducted three times.

Observation of experimental results reveals a strong linear relationship between the standard load's rotational inertia (I-I_0) and the square of the oscillation period, as illustrated in Fig.8. The slope of the curve in the figure represents the elastic coefficient D of the molybdenum wire, indicating that the use of standard loads of varying masses does not significantly stretch the molybdenum wire. This implies that D remains constant and does not affect the oscillation period of standard loads of the same mass during the experiment.

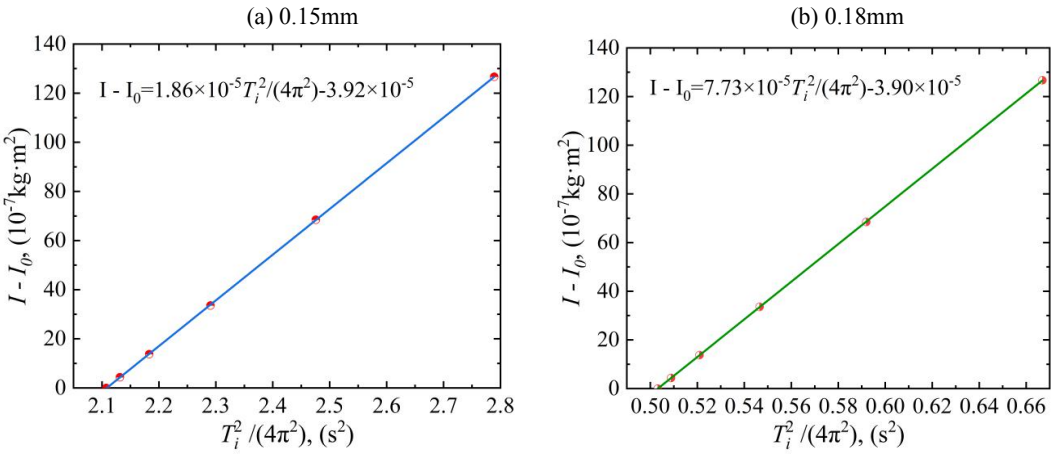

Fig. 8 Illustrates the relationship between the standard load's rotational inertia (I-I_0) and the oscillation period squared (T_2) using (a) 0.15mm and (b) 0.18mm for molybdenum wire diameter.

Our measurements show that the rotational inertia of the experimental setup's suspension system, employing a 0.15mm diameter molybdenum wire, is 3.92×10^{-5} kg·m^2, with an oscillation period T of 9.191s when no standard load is attached. Similarly, employing a 0.18mm diameter molybdenum wire, the measured rotational

inertia of the suspension system is 3.90×10^{-5} kg·m^2, and the oscillation period T without a standard load is 4.457s. Upon analysis, it is evident that the most significant factors influencing the computation results are the periods T and t_{AB}. Furthermore, our findings suggest that utilizing molybdenum wires of different diameters directly impacts the motion period of the suspension system, thereby causing significant deviations in viscosity measurement outcomes.

4.2 Uncertainty calculation

The experimental uncertainty of kinematic viscosity is a crucial parameter for evaluating the performance of the oscillating cup viscometer. Based on experimental data, the errors in the input parameters of the Shvidkovskiy equation were determined. The propagation of these errors during the calculation of kinematic viscosity was analysed. The accuracy of the final experimental results is controlled by the involved errors, and the measurement precision of each parameter is presented in Table 1.

Table 1 Measurement precision of various physical parameters

Physical parameters	Measurement accuracy
Period (T)	1 mms
Sample mass (m)	0.1 mg
Crucible inner diameter (R)	0.01 mm

In the above Shvidkovskiy model, the input parameters for calculating kinematic viscosity include the rotational inertia of the suspension system, the oscillation period and logarithmic decay rate of the empty cup, the oscillation period and logarithmic decay rate after adding the sample, the density and mass of the sample, as well as the inner radius of the crucible. To analyse the experimental uncertainty, the root mean square deviations of these parameters were determined. The relative error of the measured period was less than 0.04%, which can be neglected. The uncertainty of δ was 0.3%. Similarly, the uncertainties of the oscillation period and logarithmic decay rate of the empty cup were 0.006% and 0.2%, respectively. Meanwhile, reasonable estimates were made for the uncertainties of other input parameters. Through repeated mass measurements, the uncertainty of mass was approximately 0.4%. The uncertainty of the inner radius of the sample crucible was 0.1%. Considering thermal expansion and material changes during heating, $\Delta R/R$ was estimated to be 0.3%. The uncertainty of the

rotational inertia I of the suspension system was approximately 0.5%. Based on these values, the total uncertainty of the estimated dynamic viscosity was calculated:

$$S_{\nu}^{2} = \sum_{i} \left(\frac{\partial \nu}{\partial S_i} \right)^{2} S_{i}^{2} \tag{18}$$

where S_v represents the uncertainty of kinematic viscosity, while S_i stands for the uncertainty of each actual measurement parameter. Based on this, the total experimental error of the oscillating cup viscometer is estimated to be approximately 1.8%. Table 2 lists the uncertainties of various measurement parameters.

Table 2 Uncertainties of Various Measurement Parameters

Physical parameters	Uncertainty(%)	Physical parameters	Uncertainty(%)
Sampling period (T)	0.1	Logarithmic decay rate (δ)	0.3
Empty cup period (T_0)	0.1	Empty cup logarithmic decay rate(δ_0)	0.2
Sample mass (m)	0.4	Moment of inertia (I)	0.5
Crucible inner diameter(R)	0.3	Sample density (ρ)	0.5

5 Results and discussion

Multiple sets of experiments were conducted employing molybdenum wires with diameters of 0.15mm and 0.18mm, respectively. Time-period data was obtained for temperatures ranging from 200℃ to 650℃ under different suspended wires, with a temperature interval of 50℃. Then, based on the formulas, the kinematic viscosity and dynamic viscosity of liquid lithium were calculated for different molybdenum wires and temperatures. Finally, three sets of valid experimental results were obtained, one of which is shown in Table 3, and the remaining data is displayed within the error bars in the figures.

Table 3 Experimental values of kinematic viscosity and dynamic viscosity of liquid lithium under molybdenum wires of different diameters

T(℃)	0.15 mm molybdenum wire		0.18 mm molybdenum wire	
	ν(×10^{-6}m^2/s)	η(×10^{-4}Pa·s)	ν(×10^{-6}m^2/s)	η(×10^{-4}Pa·s)
200	1.1403	5.7820	1.0986	5.5705
250	1.0079	5.0688	0.9806	4.9317
300	0.9130	4.5539	0.9217	4.5972
350	0.8121	4.0174	0.8373	4.1417
400	0.7731	3.7923	0.7538	3.6977
450	0.6995	3.4023	0.7235	3.5190

500	0.6598	3.1821	0.6534	3.1511
550	0.6188	2.9590	0.6510	3.1127
600	0.6082	2.8834	0.6065	2.8752
650	0.5778	2.7151	0.5510	2.5891

5.1 Kinematic Viscosity of Liquid Lithium

Employing the data from reference as the standard values [17], the measured lithium densities obtained employing molybdenum wires of different diameters were compared to the standard values at various temperature points. The overall deviation is illustrated in Fig.9, where v_{exp} represents the experimental density values and v_{eq} represents the reference values. A comparison between the experimental and reference values is shown in Fig.10. It can be observed that, employing the experimental setup designed in this study, the minimum deviation in kinematic viscosity measurement was 0.507%, the maximum deviation was -3.34%, and the average deviation was 1.82%. When comparing molybdenum wires of different diameters, the molybdenum wire with a diameter of 0.15mm exhibited a minimum deviation of -0.33% and a maximum deviation of ±1.72% in kinematic viscosity measurement. On the other hand, the molybdenum wire with a diameter of 0.18mm showed a minimum deviation of 1.25% and a maximum deviation of ±3.3% in kinematic viscosity measurement.

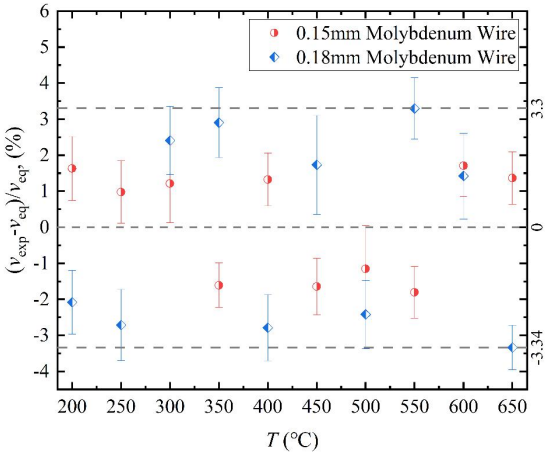

Fig.9 Experimental deviation of kinematic viscosity of liquid lithium employing molybdenum wires of different diameters

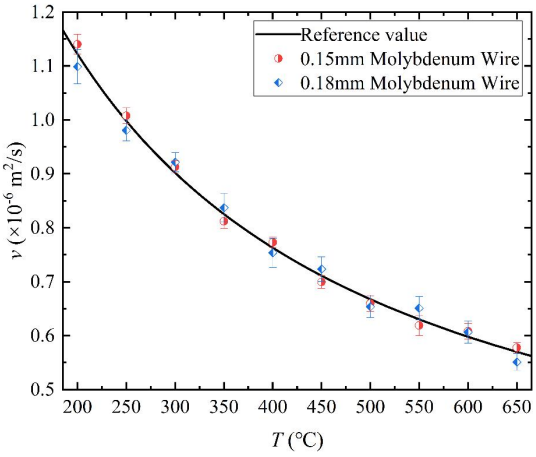

Fig. 10 Experimental values of kinematic viscosity of liquid lithium employing molybdenum wires of different diameters

Because the elastic modulus of the 0.18mm molybdenum wire is 4.16 times that of the 0.15mm molybdenum wire, the corresponding vibration period differs by 2.06 times during the empty measurement. Under the same moment of inertia, the elastic constant is proportional to the square of the period. In calculating the logarithmic decay rate, molybdenum wires with diameters of 0.18 mm and 0.15 mm were employed, respectively. For the 0.18 mm wire, the time interval between points $t_{(AB,\ i)}$ and $t_{(AB,\ i+n)}$ from the start to the end of vibration was approximately 1.3 s, with an average of 90 measured cycles. For the 0.15 mm wire, the $t_{(AB,\ i)}$-$t_{(AB,\ i+n)}$ interval was about 2.5s, yielding an average of 170 measured cycles. The longer time interval and higher number of measured cycles indicate that the vibration of the suspension system is closer to the actual resistance decay. Under a measurement time resolution of 1 ms, for the 0.18 mm wire, a 1 ms deviation in measurement $t_{(AB,\ i+n)}$ contributed to a 3% impact on the final kinematic viscosity calculation, while a 1 ms deviation in measurement $t_{(AB,\ i)}$ led to a 7-8% impact. In contrast, for the 0.15 mm wire, a 10 ms deviation in measurement $t_{(AB,\ i+n)}$ had a 2.4% impact on the kinematic viscosity calculation, and a 1 ms deviation in measurement $t_{(AB,\ i)}$ had a 3.5% impact. Statistical analysis of all measured cycles in the experiment revealed that, for identical molybdenum wire diameters and loading conditions, the time intervals between $t_{(AB,\ i)}$ and $t_{(AB,\ i+n)}$ remained constant for the first 10 cycles of the experiment, with fluctuations occurring only in subsequent cycles. Therefore, the primary influence on the calculation results stemmed from the measurement deviation of point $t_{(AB,\ i+n)}$. Fluctuations only occur in subsequent cycles, indicating that the main influence on the calculation results is the measurement deviation of. As evident from the deviation results in Fig.9, with a time measurement

resolution of 1ms, experiments employing the 0.15mm molybdenum wire yield more stable and accurate results.

5.2 Dynamic Viscosity of Liquid Lithium

The experimentally measured kinematic viscosities were calculated and compared employing both the literature reference values and the experimental values. A comparative analysis of the deviations in the calculated dynamic viscosity data is presented in Fig.11, where ρ_{exp} represents the experimental values, and ρ_{eq} represents the literature reference values. A direct comparison between the experimental values and the reference values from the literature is depicted in Fig.12.

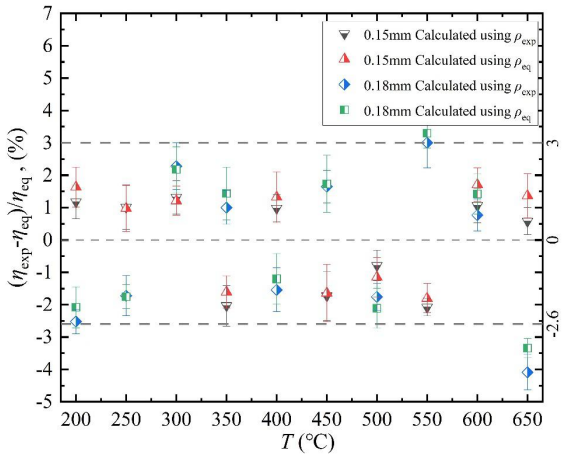

Fig. 11 Presents the experimental deviations in the kinematic viscosity of liquid lithium with molybdenum wires of different diameters

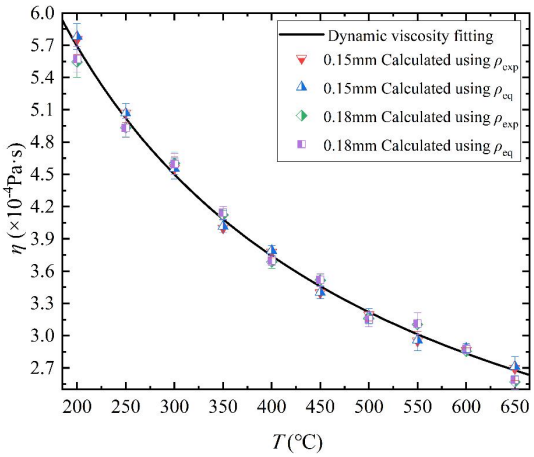

Fig. 12 Illustrates the fitting of the dynamic viscosity of liquid lithium

As observed in Fig.12, the maximum deviation of the dynamic viscosity compared to the reference literature values is 3.0%, with a minimum deviation of 0.58% and an average deviation of 1.70%. Notably, the deviation fluctuations are reduced after calculating the dynamic viscosity from the kinematic viscosity data obtained using the

0.18 mm diameter molybdenum wire, resulting in an average deviation of ±2.6%. No significant differences were observed in the dynamic viscosity data calculated using different density values.

6 Conclusion

This paper presents the development of an oscillating cup-type viscosity apparatus using Shvidkovskiy algorithm for liquid lithium over a temperature range from 200℃ to 650℃, and analyses the measurement errors and uncertainty. Some key findings include:

(1) The average deviations for kinematic and dynamic viscosities of liquid lithium in the temperature range from 200℃ to 650℃ are 1.82% and 1.70%, respectively. It proves that the developed viscosity apparatus has an acceptable measurement accuracy.

(2) The motion periods are the significant input parameter for Shvidkovskiy model. And the wire diameter is the critical factor, which can cause apparent viscosity measurement deviation by impacting the suspension system's motion period.

(3) The experimental results show that the maximum kinematic viscosity deviation using a 0.15 mm molybdenum wire is ±1.72%, which is superior to the deviation of ±3.54% with a 0.18 mm wire. It indicates the smaller diameter of wire has a better resistance to uncertainty perturbation.

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